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Future irrigation expansion outweigh groundwater recharge gains from climate change in semi-arid India

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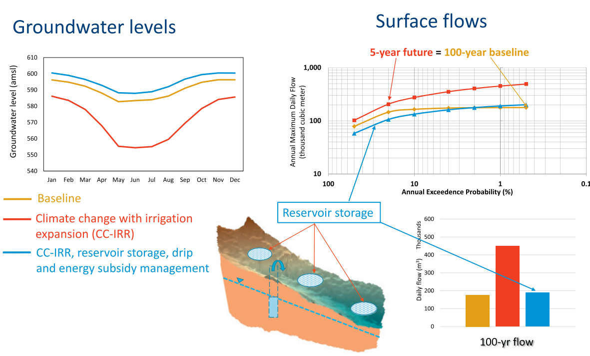
HIGHLIGHTS

- Predicted increase in future rainfall increased groundwater recharge.
- Future irrigation expansion negated the positive groundwater recharge effects.
- Increased well drying under changed climate with irrigation expansion
- Increased frequency of extreme flow events (e.g., flooding) in the future
- Energy subsidy reforms needed to fund water storage and drip irrigation

GRAPHICAL ABSTRACT



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ABSTRACT

Simultaneous effects of future climate and irrigation intensification on surface and groundwater systems are not well understood. Efforts are needed to understand the future groundwater availability and associated surface flows under business-as-usual management to formulate policy changes to improve water sustainability. We combine measurements with integrated modeling (MIKE SHE/MIKE11) to evaluate the effects of future climate (2040–2069), with and without irrigation expansion, on water levels and flows in an agricultural watershed in low-storage crystalline aquifer region of south India. Demand and supply management changes, including improved efficiency of irrigation water as well as energy uses, were evaluated. Increased future rainfall (7–43%, from 5 Global Climate Models) with no further expansion of irrigation wells increased the groundwater recharge (10–55%); however, most of the recharge moved out of watershed as increased baseflow (17–154%) with a small increase in net recharge (+0.2 mm/year). When increased rainfall was considered with projected increase in irrigation withdrawals, both hydrologic extremes of well drying and flooding were predicted. A 100-year flow event was predicted to be a 5-year event in the future. If irrigation expansion follows the historical trends, earlier and more frequent well drying, a source of farmers' distress in India, was predicted to worsen in the future despite the recharge gains from increased rainfall. Storage and use of excess flows, improved irrigation efficiency with flood to drip conversion in 25% of irrigated area, and reduced energy subsidy (free electricity for 3.5 h compared to 7 h/day; $1 billion savings) provided sufficient water savings to support future expansion in irrigated areas while mitigating well drying as well as flooding. Reductions in energy subsidy to fund the implementation

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of economically desirable (high benefit-cost ratio) demand (drip irrigation) and supply (water capture and storage) management was recommended to achieve a sustainable food-water-energy nexus in semi-arid regions.

1. Introduction

Changes in temperature, precipitation and other climatic variables during 20th century (Donat et al., 2013; McVicar et al., 2012; Mishra et al., 2015; Wild, 2009; Willett et al., 2008) have altered the surface and groundwater systems globally (Stocker et al., 2013). Future changes in the climate are likely to affect surface flows (Vano et al., 2015; Van Vliet et al., 2013), groundwater recharge (Crosbie et al., 2013; Doll, 2009) and water availability in many parts of the world. At the same time, increased food demand due to demographic, cultural and socio-economic changes is likely to increase the future water demands (Sauer et al., 2010; Vörösmarty et al., 2000). For example, in India, under the "business-as-usual" scenario, 40% increase in groundwater withdrawals has been predicted for 2050 compared to the base year 2000 (Amarasinghe et al., 2007). The "business as usual" scenario in Amarasinghe et al. (2007) was based on the recent trends in population and agriculture growth and assumes rather optimistic future economic growth with increasing per capita food and water consumption. Climate change will occur simultaneously with these societal changes; therefore, climate change impact and adaptation studies must also consider changing land and water demands (Holman et al., 2012; Woldeamlak et al., 2007). Depending on the direction of change (e.g. increased or decreased rainfall), future climate may either support the increased water demands or further worsen the water availability.

Globally, groundwater provides drinking water to >50% of population (≈3.5 billion, Connor, 2015) and supports 40% of irrigated areas (Siebert et al., 2010). Groundwater supply is even more critical for arid and semi-arid regions (e.g. western United States and most of India). For example, in India, groundwater provides drinking water supply to one billion people (World Bank, 2010), supports 65% of irrigated agriculture (Siebert et al., 2010), and contributes 9% to the gross domestic product (Sharda et al., 2006). However, lack of data and uncertainties related to the complex and slow response of groundwater systems to changing climatic conditions have limited the evaluation of climate change effects on groundwater (Field et al., 2014; Zektser and Dzyuba, 2015). Furthermore, climate change impact studies using hydrologic modeling have not considered future changes in groundwater demand due to irrigation expansion related to demographic, societal and land use changes (Beigi and Tsai, 2015; Crosbie et al., 2013; Goderniaux et al., 2009; Scibek and Allen, 2006).

India is the largest groundwater user (250 billion m^3/year) (AQUASTAT, 2010) in the world and contributes to >25% of global annual withdrawals (World Bank, 2010). Increased climatic variability in the future (e.g. more frequent droughts) may further promote the groundwater use as a potential adaptation measure (Scott, 2013; Taylor et al., 2013). Many of the semi-arid regions, including the Indo-Gangetic plain and crystalline aquifers in central and south India, are already experiencing groundwater depletion and other environmental problems (Palanisami et al., 2008; Panda and Wahr, 2016; Rodell et al., 2009; Sishodia et al., 2016). Increased groundwater demands due to climatic and societal changes coupled with limited rainfall and adaptation capacity (Mertz et al., 2009) may worsen the groundwater supply in the crystalline aquifer region of central and south India (Sishodia et al., 2017). In the past, well drying, crop losses and increasing debts (e.g. loan financed for well installation) due to recurring droughts have caused many farmers in this region to commit suicide (Mohanty and Shroff, 2004; Rao and Suri, 2006). Many of the farmers resorted to well deepening or installation of deeper drilled wells to cope up with the declining groundwater levels in this region. Current regulations do not permit new well drilling in areas designated as over exploited, however the regulations are seldom followed due to lack of coordination between government agencies (Sishodia et al., 2016). Considering limited storage capacity of the shallow crystalline aquifers (Dewandel et al., 2006), management and policy changes targeted towards increasing the irrigation efficiency will be needed to support the projected expansion in irrigated area.

A few studies have been conducted in India to evaluate the effects of climate change and irrigation on groundwater recharge and availability (Ferrant et al., 2014; Sekhar et al., 2013; Surinaidu et al., 2013); however, simultaneous expansion in irrigation have not been considered to evaluate the combined effects on surface and groundwater flows and levels. For example, Ferrant et al. (2014) used the SWAT model (Gassman et al., 2007) to predict the effects of climate change on groundwater use and availability for a crystalline aquifer catchment (area = 983 km^2) in south India; however, they did not account for future changes in groundwater demand driven by changing demographic or socio-economic conditions. As opposed to focusing on either surface water or groundwater (Surinaidu et al., 2013), for basin-scale water availability assessments surface water and groundwater must be treated as an integrated system. Both surface water and groundwater play a critical role in providing water supply for agriculture, industrial, domestic sectors in India (Thatte, 2017) and the world. Evaluation of the combined effects of future climate and irrigation expansion on surface and groundwater system, followed by hydrologic and economic assessment of management and policy changes have not been conducted in India. Future changes in surface and groundwater flows brought by changed climate and irrigation are likely to influence existing management and government policies to mitigate the adverse effects on water availability (Sivapalan, 2015). In this study, we use an integrated hydrologic model to predict the effects of changes in future climate, irrigation, management and policy on surface and groundwater availability for a representative agricultural watershed in semi-arid south India. Specific objectives were to: 1) evaluate the effects of future climate, with and without irrigation expansion, on groundwater recharge, levels and surface flows and 2) evaluate the hydrologic and economic impacts of management and policy changes under changed future climate and irrigation demand to improve water sustainability.

2. Materials and methods

2.1. Study site

Integrated hydrologic models usually require extensive long-term weather, land use, irrigation, surface flows, soils, hydrogeology, and groundwater levels data, which are rarely available for Indian watersheds (Adamowski et al., 2012). International Crops Research Institute for Semi-Arid Tropics (ICRISAT) has one such well-studied watershed in south India where additional hydrologic and land use data were collected for this study. The study site, Kothapally watershed, is located at 17° 22′N latitude 78° 07′E longitude in the semi-arid Telangana state of south India (Fig. 1). The watershed elevation ranges from 600 to 640 m above mean sea level. The watershed (320 ha) is a part of the Musi river sub-basin which is a tributary of the Krishna River. Average annual rainfall (2000–2012) is 840 mm, 85% of which is received during the monsoon season (June–October). Rainfall exhibits high inter annual variability, for example annual rainfall varied from 571 mm in 2002 to 1352 mm in 2008. Surface flow in streams is mostly limited to the monsoon season. The maximum temperature climbs to 44 °C during summer (April–May) and minimum temperature dips to 6 °C in winter (November–February). Crops in the region are mainly grown during

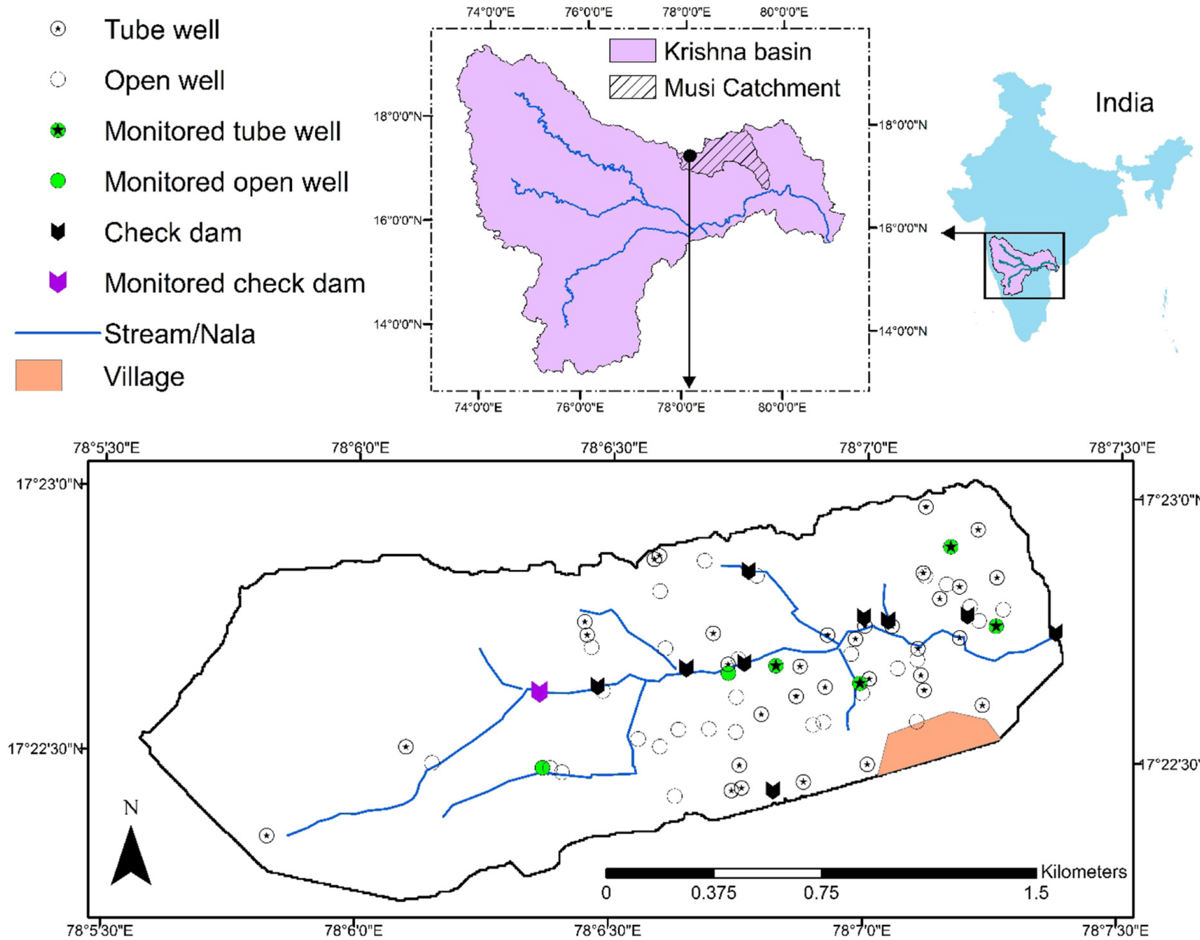

Fig. 1. Location of the Kothapally watershed in Krishna River basin. Locations of existing irrigation wells, stream network, in-stream check dams and monitoring wells are also shown.

Kharif (June–October, wet monsoon season) and *Rabi* (November–February, dry season) seasons. Summer (March–May, dry season) crops may also be grown depending on groundwater availability. Cotton is typically planted during the *Kharif* season and vegetables (e.g. tomato, peppers and carrots) are grown during the *Rabi* and summer seasons. Primary occupation of most households in the watershed is farming and almost three-quarters of watershed area is cropped during the monsoon season. Close proximity (≈20 km) to capital city of Hyderabad (2011 population = 6,809,970) helps farmers in the watershed and surrounding area fetch good prices for fresh market and other agricultural produce. Agriculture is an important sector in the state of Telangana as more than half of the population is dependent on it (GOT, 2016).

2.2. Simulation of climate change and irrigation expansion

2.2.1. Hydrologic modeling

MIKE SHE/MIKE 11 (Graham and Butts, 2005; Jaber and Shukla, 2012), a physically-based distributed hydrologic model developed from SHE (Système Hydrologique Européen) (Abbott et al., 1986a,b) was used in this study to simulate the land phase of the hydrologic cycle. MIKE SHE/MIKE 11 have been shown to work effectively under different climate and hydrologic regimes (mountainous to coastal and shallow to deep groundwater) across all continents to evaluate the effects of land use and climate change on groundwater and surface water flows (Demetriou and Punthakey, 1999; Jaber and Shukla, 2004; Im et al., 2009; Stoll et al., 2011; Vansteenkiste et al., 2013; Wijesekara et al., 2012). The main components included in the integrated MIKE SHE/MIKE 11 model were evapotranspiration, overland flow, unsaturated zone flow, saturated zone flow and river flow (MIKE11). In MIKE 11, a fully dynamic finite difference solution of the St. Venant equations was used to simulate flow in open channels (Havnø et al., 1995; Jaber and Shukla, 2012). Dynamic coupling of MIKE SHE with MIKE 11 allows for bi-directional exchange of fluxes between river, overland, saturated and unsaturated zone components. Actual ET was estimated by the Kristensen and Jensen method which uses input crop coefficient (Kc), leaf area index (LAI), root depth (RD) and model simulated soil moisture. Diffusive wave approximation of 2-D Saint Venant equations was used to simulate overland flow. Saturated and unsaturated zone fluxes were simulated by a fully implicit finite difference solution of 3-D Darcy equations and 1-D Richards' equation, respectively.

Based on the resolution of the available land use data, 45 × 45 m grid size was used in this study; this grid size closely represents a typical farming parcel size in the watershed and therefore captures the spatial variability in crop, soil and water management. Topography of the watershed was generated using the total station survey data of the watershed covering >4200 survey points (Table 1). Weather, stream network, soils, land use, irrigation and geologic data collected during 2009–2014, were used to set-up the MIKE SHE/MIKE 11 model. The data used for model set up and parametrization are provided in Tables 1 and 2, respectively.

2.2.1.1. Weather, land use and irrigation. Daily rainfall data were collected by an automatic weather station in the watershed installed in 2000. Reference ET, a required model input, was calculated using the Food and Agriculture Organization's "ET_o Calculator" software (Raes, 2012, Table 1). The dominant crop in the watershed is rainfed cotton (56% of area) grown during June–January. The irrigated crop rotations and

Table 1
Description of data used to set up MIKE SHE/MIKE 11 model.

Component	Data	Source	Time period
Topography	DEM	Total station survey (Garg et al., 2012)	
Weather	Daily data • Temperature • Humidity • Wind Speed • Solar radiation	International Crops Research Institute for Semi-Arid Tropics (ICRISAT) weather station (25 km from Kothapally)	2009–2014
	• Daily rainfall	Kothapally weather station	2009–2014
Land use	• Crop rotation • Cropped area	• Farmer survey • Field visits • Satellite images	2009–2014
Overland and streamflow	• Detention storage • Stream cross sections • Check dam dimensions	Topographic survey	
Soil	• Depth • Texture • Bulk density • Field capacity • Wilting point	Up to 1.5 m deep soil sampling at 50 locations in the watershed	

growing periods include cotton-vegetable (11%, June–April), vegetable-vegetable-vegetable (6%, June–May), and paddy-vegetable (3%, June–April). The remaining watershed area (24%) is classified as barren land. Irrigation was applied based on the available soil moisture content except for the paddy-vegetable rotation. Irrigation in the paddy-vegetable was applied at a rate of 7.2 mm and 3.2 mm per day for paddy (*Kharif*) and vegetables (*Rabi*), respectively based on the current practice in the watershed. Except for paddy-vegetable, irrigation was applied when available soil moisture (difference between actual moisture and wilting point) reached 40% and 50% of maximum available moisture (difference between saturation and wilting point) during the *Kharif* and *Rabi* seasons, respectively. MIKE SHE doesn't have an explicit crop growth module and uses input crop information (crop coefficient, leaf area index and root depth) to simulate crop water use or transpiration based on the available soil moisture.

Irrigation withdrawals constitute a significant fraction of the water balance in the semi-arid hard rock region of India and the absence of measured irrigation data can introduce large uncertainty in surface and groundwater storage predictions. Measured flow rates (PORTAFLOW-C, Fuji Electric Co. Ltd., Tokyo, Japan) from six open wells and 15 tube wells recorded during November 2012 were used to estimate daily maximum pumped volume from individual wells. Observed variability in flows from open wells (23–36 $m^3 h^{-1}$) and tube wells (6–27 $m^3 h^{-1}$) indicates that surveys and single pump measurement based irrigation withdrawal estimates, usually employed in agriculture irrigation studies in the hard rock aquifer region, are likely to be erroneous. Pressure transducers (Levelogger, Solinst Canada Ltd., Ontario, Canada), hereafter termed as level loggers were installed in seven wells (Fig. 1) to measure groundwater levels and daily pumping hours during 2012–2014. Measured groundwater level fluctuations indicated approximately 700 and 200 h of annual pumping from tube wells and

Table 2
MIKE SHE/MIKE 11 model parameterization for the Kothapally watershed.

Parameter	Value or range		Source
Saturated soil hydraulic conductivity (m/s)	1×10^{-7} to 5×10^{-6}		Calibrated
Saturated and residual soil moisture contents (θ_s and θ_r, v/v)	$\theta_s = 0.45$ to 0.55 $\theta_r = 0.06$ to 0.09		Estimated from ROSETTA (Schaap et al., 2001)
Van-Genuchten model soil parameters	$\alpha = 0.002$ to 0.03 $n = 1.13$ to 1.91 $l = -1.34$ to 0.50		Estimated from ROSETTA (Schaap et al., 2001)
Leaf area index (LAI), root depth (RD) (mm) and crop coefficient Kc	Cotton (maximum)	LAI - 3.5 RD - 900 mm K_c - 1.05	Literature (Allen et al., 1998; Al-Khafaf et al., 1978; Bland, 1993; Mohan and Arumugam, 1994)
	Vegetable (maximum)	LAI - 2.5 RD – 500 mm K_c - 1.1	
Manning's number for overland flow (M = 1 / n)	8		Garg et al. (2012)
Saturated zone layers' hydraulic conductivity (m/s) - Horizontal and vertical	Top weathered - 5×10^{-5} and 4×10^{-6} Middle impermeable - 5×10^{-9} and 5×10^{-9} Lower fractured - $3 \times 10^{-5}$and 3×10^{-6}		Calibrated
Specific yield	Top weathered - 0.02 Middle impermeable - 0.001 Lower fractured - 0.0015		Calibrated
Specific storage (1 / m)	Top weathered - 3×10^{-5} Middle impermeable - 1×10^{-6} Lower fractured - 2.6×10^{-5}		Calibrated
Leakage coefficient for stream-aquifer exchange (per second)	3×10^{-6}		Calibrated

open wells, respectively. Measured flow rates and average pumping hours provided an estimated pumping rate of 165 mm/year in the watershed during 2012–2014. Irrigation parameters (e.g. daily maximum pumping and soil moisture based irrigation trigger) were adjusted in MIKE SHE to match the simulated annual irrigation (155 mm) with estimated current (2012–2014) annual pumping volume (165 mm).

2.2.1.2. Overland and streamflow. As part of a watershed development program, 14 check dams and percolation ponds were constructed in Kothapally during 1999–2003 (Garg et al., 2012). These structures were installed to reduce erosion, retain runoff and enhance groundwater recharge. The constructed runoff storage structures increased the watershed storage capacity by 13,000 m^3. As of 2014, there were 27 constructed and natural soil and water management structures including check dams, percolation ponds, farm ponds and gully control structures. Seven in-stream check dams were simulated as broad crested weirs in MIKE 11 (Fig. 1). Streamflow at the watershed outlet was calculated from measured surface water levels and a weir equation. A head-discharge boundary condition based on the weir flow equation was used at the main outlet weir of the watershed. Detention storage in MIKE SHE was set to 2 mm except for the locations of percolation ponds where it was adjusted to reflect the measured storage capacity of the dispersed percolation ponds in the watershed. A uniform value of 8 was used for Manning's number ($M = 1 / n$) based on an earlier modeling study in the watershed (Garg et al., 2012).

2.2.1.3. Soils and geology. Shallow to moderately deep (20 cm to 2 m) soils in the watershed have been classified as predominantly Vertisols with clay to sandy clay loam texture (Wani et al., 2003). The watershed was divided into eleven zones to represent the variability in soil depth and properties (Table 2). The saturated zone in the Kothapally watershed is composed of three distinct layers; a top weathered layer, a middle compact layer and a lower fractured layer extending up to 120 m below ground (Table 2). The thickness of the upper weathered layer, where open wells are located, was assumed to be uniform (14 m) throughout the watershed based on the average depth of open wells in the watershed. The thickness of the middle impermeable layer ranged from 0.5 to 20 m, with higher values in uplands. A closed boundary condition was used for all saturated zone layers i.e. no groundwater flux exchange between the watershed and surrounding region because the basin or watershed boundaries in these hard-rock regions usually coincide with the groundwater flow boundary (Limaye, 2010).

2.2.1.4. Model calibration and validation. Model calibration was performed manually with measured groundwater levels in six wells (two open and four tube wells, 2012–2013) and surface water levels behind one check dam (2012–2013) (Fig. 1). Measured groundwater levels in the six monitoring wells during 2013–2014 and daily streamflow (2009–2014) were used for model validation. Pumping introduces significant uncertainty in instantaneous water level measurements; therefore, observed daily maximum groundwater levels were used for model calibration and validation. Observed 15-minute level logger data showed that water levels in the tube wells rise back to a stable level 3–4 h after pumping ceases. Provision of a maximum 6–7 h of free electricity per day limits the pumping hours because all the wells are electric powered in the watershed. The daily maximum levels in the monitored wells should therefore reasonably represent the natural (un-pumped) groundwater levels in the surrounding area.

Literature review (Jaber and Shukla, 2012; Im et al., 2009; Wijesekara et al., 2012) and preliminary model runs with different sets of parameters helped identify the model calibration parameters (Table 2). The most sensitive and uncertain parameters (e.g. soil saturated hydraulic conductivity - K_{sat}) were calibrated first and other parameters (e.g. aquifer K_{sat}, specific yield, storage and stream-aquifer leakage coefficient) were adjusted later to find the best match between observed and simulated groundwater and surface water levels. For calibration, a plausible range of these parameters was determined from the literature (Dewandel et al., 2006; Garg et al., 2012; Maréchal et al., 2006). Nash Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE) and percent bias (PBIAS) were used to evaluate the model performance. Model performance was rated based on the criteria in Moriasi et al. (2007) where NSE values between 0.65 and 0.75 indicate "good" model performance, while NSE values > 0.75 indicate "very good" model performance. Simulated daily surface and groundwater levels showed that the model captured seasonal and annual fluctuations in groundwater levels with "good" to "very good" ratings for the calibration and validation periods (Table 3). MIKE SHE/MIKE 11 was able to successfully represent the rise of groundwater levels in wet season (June–Oct) and fall of groundwater levels in dry season (Nov–May) in response to rainfall and pumping, respectively. Majority of rainfall (85%) occurs during the wet season (monsoon) while majority of pumping (75%) occurs during the dry season in the watershed.

2.2.2. Climate change and irrigation expansion scenarios

The Agricultural Model Intercomparison and Improvement Project (AgMIP) methodology (Ruane et al., 2015) was used to generate the mid-century (2040–2069) climate time series (temperature and precipitation) for the Representative Concentration Pathway (RCP) 8.5 (Riahi et al., 2011). The AgMIP climate scenario generation methods have been used globally to assess the climate change impacts on agriculture (Araya et al., 2015; Rahimi-Moghaddam et al., 2018; Rosenzweig et al., 2013). Five Global Climate Models (GCMs) from the Coupled Model Intercomparison Project 5 (CMIP5) were used to generate the future climate scenarios for this study (Table 4). These GCMs were selected based on their ability to simulate the Indian/South Asian monsoon climate (Ruane et al., 2015). Earlier versions of Hadley center, MIROC and MPI models performed reasonably well in simulating the south Asian monsoon climate (Kripalani et al., 2007; Sabade et al., 2011). As compared to CMIP 3 versions, most of the CMIP 5 models including CCSM4 and GFDL have shown improved skill in simulating the Indian monsoon (Delworth et al., 2012; Meehl et al., 2012; Sperber et al., 2013).

The AgMIP methodology uses a modified delta method to downscale climate model predictions (Ruane et al., 2015). While the basic delta method applies only mean monthly changes (GCM simulated future climate variables minus simulated historical climate variables) to the observed baseline or historical time series (Hay et al., 2000; Yu et al., 2010), the AgMIP method used in this study also allows for changes in temperature and rainfall variability and frequency (Ruane et al., 2015). Thus, this method allows for greater rate of changes in extreme events, compared to average events, and also changes in number of rainy days (Ruane et al., 2015). By applying mean and variability changes to the historical time series, rather than directly using the GCM generated future time series, this method also removes GCM biases. Future reference ET for MIKE SHE input, was calculated with "ET_o Calculator" software (Raes, 2012) based on the future projected temperature.

The calibrated and validated MIKE SHE/MIKE 11 model was used to build the climate change and irrigation expansion scenarios presented in Table 5. In this paper, GCM specific climate change (CC) and climate change with irrigation expansion (CC-IRR) scenarios are referred by the name of the GCM used to generate the future climate series e.g. CCSM4 scenario. Future irrigation expansion projections were based

Table 3
Model performance statistics for the calibration (6/2012–5/2013) and validation (6/2009–5/2014) periods.

Period	Target	NSE	RMSE (m)	PBIAS (%)
Calibration	Groundwater levels	0.67–0.79	0.86–2.7	−0.008 to −0.10
	Surface water levels	0.76	0.16	−0.001
Validation	Groundwater levels	0.73–0.95	0.62–1.6	−0.00002 to −0.15
	Streamflow	0.87	0.03	−13

Table 4
Global climate models (GCMs) used to generate future weather time series (2040–2069).

GCM	Agency
CCSM4 - Community Climate System Model (Gent et al., 2011)	National Centre for Atmospheric Research (NCAR), USA
GFDL-ESM - Geophysical Fluid Dynamics Laboratory model (Dunne et al., 2012, 2013)	National Oceanic and Atmospheric Administration (NOAA), USA
HadGEM2-ESM - Hadley Centre Global Environment Model (Collins et al., 2011)	Met Office Hadley Centre, UK
MIROC5- Model for Interdisciplinary Research on Climate (Watanabe et al., 2011)	Multiple Japanese agencies including Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Japan
MPI-ESM - Max Plank Institute's Earth system model (Giorgetta et al., 2013)	Max Plank Institute, Germany

on the historical trends in expansion of tube wells in the region. Trends during 1993–2007 showed an average expansion rate of 36 and 24 wells/100 km^2/year at the district and state level, respectively (DES, 2013a). A slightly lower expansion rate of 20 wells/100 km^2/year was used for the study area. This smaller expansion rate was assumed because the potential for new wells may be limited in the future due to existing groundwater development and rates of well failures that are occurring in the hard rock aquifer region (Kumar et al., 2011; Reddy, 2005). Irrigated areas in MIKE SHE/MIKE 11 were increased to reflect the increase in the number of tube wells by replacing rainfed cotton and fallow barren lands with irrigated crops (e.g. cotton-vegetable, paddy- vegetable and vegetable-vegetable-vegetable rotations). Studies have reported a decline in area irrigated per well during 1993–2007 coinciding with an increase in the number of tube wells in the state (Sishodia et al., 2016). Considering this anticipated future decrease in the irrigated area per well because of reduced water availability, the new tube wells in future scenarios were assumed to support 1–1.2 ha of irrigated area in the dry season rather than 1.2–1.6 ha under the current scenario. Irrigation application methods (e.g. irrigation trigger) were kept same as to the calibrated model.

2.3. Future water management strategies

2.3.1. Supply management

In view of increased rainfall projections for India (Menon et al., 2013; Turner and Annamalai, 2012), government and society may promote supply management strategies such as capture and storage of excess water to increase water availability as well as to reduce downstream flooding damage in the future. Increased dispersed water storage through increased check dam storage was achieved by doubling the height of the seven existing in-stream check dams. In places where the topography did not permit sufficient height increase above the existing crest level, the bottom of the stream was lowered to achieve the doubling of the check dam storage. Lowering of the stream bottom could be achieved by dredging the channel. The existing design capacity of the seven check dams permits storage of 6400 m^3 (2.2 mm) while the modified height of these check dams almost doubled their water holding capacity to 12,600 m^3 (4.4 mm).

Increased watershed storage by dispersed percolation ponds was simulated by increasing the detention storage in MIKE SHE/MIKE11. In MIKE SHE, the detention storage is used to represent small depressions and ponds in the watershed. Overland flow is simulated once the depth of ponded water in a cell exceeds the detention storage. In effect, increasing detention storage in MIKE SHE/MIKE 11 is equivalent to capturing water in small depressions and/or ponds. Detention storage was increased by 1 mm throughout the watershed which is equivalent to capturing 3000 m^3 (1 mm) of additional water in ponds or depressions. Presently there are 12 constructed percolation ponds approximately 6 m × 6 m × 1 m in size, excluding the natural (or modified-natural) farm ponds or depressions. Thus the proposed increase of 3000 m^3 in storage is equivalent to constructing 80 new percolation ponds of this size.

To simulate the streamflow capture in MIKE SHE/MIKE 11, three large, unlined side reservoirs (400,000 m^3 capacity each) were placed along with the existing in-stream check dams at upland, middle and lowland locations of the watershed. To reduce the evaporation losses, each reservoir was divided into two cells, cell 1 and cell 2 with a capacity of 150,000 and 250,000 m^3 respectively. Once cell 1 (1.15 ha, 13 m deep) was filled, captured streamflow water was diverted to the cell 2 (1.9 ha, 13 m deep). This arrangement reduces the water surface area and hence evaporation. Streamflow above a specified elevation on the check dams was diverted to the stream-side reservoirs. These specified elevations for each of the three check dams were fixed such that the annual streamflow at the watershed outlet was not lower than the baseline.

2.3.2. Integrated supply and demand management

Future adaptation to demand management strategies such as drip irrigation and electricity subsidy reduction was evaluated in combination with excess flow capture. Free or subsidized electricity has been cited as a major cause of increased groundwater withdrawals and depletion in India (Shah et al., 2012; Sishodia et al., 2016), therefore future reductions or reforms in energy subsidy are likely. Irregular and night time electricity hours in combination with inefficient flood irrigation result in electricity wastage and reduce irrigation efficiency by promoting unproductive soil evaporation, seepage and deep percolation losses. To simulate future demand management policies in the region, a 50% reduction in energy subsidy (3.5 h compared to 7 h of daily free electricity) was simulated by reducing the daily maximum irrigation pumpage by 50% in the MIKE SHE/MIKE 11.

To simulate existing flood irrigation in MIKE SHE, the irrigation was applied to saturate the soil when available soil moisture (difference between actual moisture and wilting point) reached at 40% and 50% of maximum available moisture (saturation minus wilting point) during the *Kharif* and *Rabi* seasons, respectively. Drip irrigation in MIKE SHE was simulated by triggering the irrigation based on the ET deficit and filling the soil to field capacity (instead of saturation under the flood method); irrigation was triggered when actual ET dropped below 90% of reference ET. This method may slightly underestimate the water savings from drip conversion (because it doesn't fully simulate the reduction in soil evaporation from crop row middles); however, MIKE SHE is not currently able to simulate the partial area (root zone) wetting.

2.3.3. Economics of management strategies

Crop damage is likely to occur under water stress conditions that will arise due to well drying in the future, especially during the dry season. Well drying will directly limit the irrigation water available for dry season crops thereby affecting the crop development and yield. A tube well was considered dry when the groundwater depth was lower than the well depth, and an open well was considered dry when the water

Table 5
Description of climate change and groundwater withdrawals scenarios evaluated in MIKE SHE/MIKE 11.

Scenario	Global climate models (GCM)	Time period	Number of wells
Baseline	None (historical weather data used)	1980–2009	37 (current 2014)
Climate change only (CC)	Five GCMs (Table 4)	2040–2069	37 (current 2014)
Climate change with irrigation expansion in future (CC-IRR)	Five GCMs (Table 4)	2040–2069	61 (expansion rate of 20 wells/100 km^2/year)

table dropped 10 m below ground surface. Crop damage and yield losses under different management options were estimated using the predicted well drying duration for all tube wells in the watershed. If a well became dry during the last 20 days of the growing season, it was assumed to not significantly affect the crop yield because farmers would have already harvested vegetables such as tomato or pepper (growing period = 120 days). Partial crop damage (30% yield loss) was assumed to occur when a well was dry during the final 20–40 days of the growing season; farmers are likely to get three pickings (out of four) for vegetables such as pepper under this scenario. Major crop damage (70% yield loss) was assumed to occur if the well was dry during >40 of the final days of the growing season; farmers are likely to lose about three vegetable pickings (out of four) under this scenario. Yield and income losses for no intervention were compared with those under different demand and supply management strategies under CC-IRR scenarios.

Yield and income losses were estimated for cotton (*Kharif*), pepper (*Kharif*) and tomato (*Rabi* and summer season) which are commonly grown crops in the watershed and state. Average reported yields (1.2, 3.7 and 14 ton/ha) and market prices ($658, $1122, and $160/ton) (US $1 = 54 ₹) for cotton, pepper and tomato during 2012–2013 were used to calculate the income losses under different management scenarios (DES, 2013b). Estimated seasonal yield losses (partial = 30%, major = 70%) were multiplied with 2012–2013 market prices to calculate average annual income losses for dry (annual rainfall < 80% of average), normal (annual rainfall is between 80 and 120% of average) and wet (annual rainfall > 120% average) rainfall years using model predicted well drying for CC-IRR scenarios (2040–2069). Reduced income (yield) losses under the management strategies were considered as net benefits and were used to calculate the benefit-cost ratio (Eq. (1)), except for the streamflow capture (reservoir) management. Net benefits under the streamflow capture and use were taken as 30% of total crop income from reservoir-irrigated areas i.e. assuming 30% net profit from higher crop production arising from reservoir-irrigated areas (GOI, 2014). Only irrigated crops (tube well and reservoir) were considered to calculate the net benefits under different demand and supply management scenarios using reported crop yields and prices in 2012–2013 (DES, 2013b).

$$Benifit-cost\ ratio = \frac{Average\ annual\ net\ benifts}{Average\ annual\ total\ cost\ (capital + operational)} \quad (1)$$

Construction cost of storage structures and installation cost of drip irrigation were included for economic evaluations. Construction costs of check dams, percolation ponds and large storage reservoirs were taken as $2.9, $0.97 and $0.97/m^3 of storage capacity, respectively; these costs were estimated from Goel and Kumar (2005) and Wani et al. (2003) with cumulative inflation adjustment of 95% for 2003–2012. Installation cost of drip irrigation was taken as $1600/ha with a service life of 10 years; 20% of the installation cost was added as repair and maintenance or operational cost during the service life (Kakhandaki et al., 2012). The service life of check dams, percolation ponds and reservoirs was assumed to be 20 years with lifetime maintenance cost being 10% of capital cost (Goel and Kumar, 2005). Total cost (capital and operational) for each management implementation was divided with corresponding service life to estimate average annual cost at 2012–2013 prices (Eq. 1). The benefits of subsidy reduction (electricity savings) were not accounted for in the benefit-cost ratio calculation because famers do not directly realize the electricity savings, although state utilities and government do benefit.

3. Results and discussion

3.1. Water budget

3.1.1. Climate change (CC) only

Compared to the baseline rainfall (1980–2009, 899 mm), all GCMs predicted increased annual rainfall under the future climate (2040–2069) (Table 6). HadGEM2 model predicted highest increase (43%, 391 mm), while GFDL-ESM predicted lowest increase (7%, 67 mm). This increase in rainfall was not consistent across seasons. The HadGEM2 model predicted high rainfall increases during the monsoon (July–October, 61–117 mm); however, it predicted 17% (19 mm) reduction in June rainfall (Fig. 2). Reduced rainfall during the June month, which is the planting time for *Kharif* season crops, may cause soil moisture stress, seedling death and delayed planting, ultimately leading to crop income loss in rainfed areas. During the dry season, the MPI-ESM and HadGEM2 models predicted 200% (43 mm) and 102% (22 mm) increase, respectively for March rainfall although remaining three GCMs predicted a decrease. Increased rainfall during February–April is likely to reduce the dry season irrigation water requirements, thereby reducing the stress on groundwater reserves. On an average, over the 5 GCMs used in this study, significant increases in future rainfall were predicted for July (40 mm), August (31 mm), September (36 mm) and October (38 mm) months.

In response to increased rainfall, streamflow (Fig. 3A) increased under all climate change (CC) scenarios (Table 6). On average, almost 75% of the increased rainfall was converted into streamflow while the rest was lost through ET. For the HadGEM2 scenario, a 186% increase in annual streamflow was predicted; however, much lower (29–68%) increases in streamflow were predicted for the remaining CC scenarios (Table 6 and Fig. 3B). On average, a large increase in average monthly streamflow was predicted for the second half of the monsoon (August = 34 mm, September = 30 mm and October = 29 mm) (Fig. 3A). Due to high antecedent soil moisture conditions, all of the increased rainfall during August was converted into streamflow and >75% of the increased rainfall was converted into streamflow during September and October. The highest proportional increase in streamflow was predicted for June (Fig. 3B); however, the absolute increase was very small (2.25 mm) as compared to the remaining monsoon months. Excess surface flow during the second half of the monsoon, when water is not usually scarce, is not likely to increase the water availability for irrigation unless stored for later use. In addition, increased peak and daily maximum flows during wet years may increase flooding risk in the downstream areas.

Almost all (92%) groundwater recharge occurred during the wet season, and >75% of pumping occurred during the dry season. Pumping volume reduced slightly in response to increased rainfall during Sept-Nov; however, it increased during Jan- May in the dry season. Average annual dry season pumping increased by 4–10 mm (3–10%), except for the MPI-ESM scenario. Despite increased temperature and ET under the MPI-ESM scenario (Table 6), average annual dry season pumping (106 mm) was almost the same as baseline (107 mm) mainly due to a 200% increase in February and March rainfall (February = 21 mm, March = 43 mm). Overall, predicted future increase of 1.5 to 2.7 °C in average temperature resulted in increased annual ET and irrigation volume (Table 6). Although groundwater recharge increased under all CC scenarios almost all of this increased recharge moved out of watershed as baseflow resulting in no significant change in net recharge (+0.2 mm; Table 6). Higher water table due to increased groundwater recharge resulted in higher baseflow contribution to the stream especially during wet years. Despite an overall increase in average recharge, net groundwater recharge was negative during dry and normal rainfall years during which most of the farmers' distress occurs. Higher groundwater demand and lower recharge reduces the water availability during dry years compared to wet years. In addition, low storage capacity of the crystalline aquifer promotes baseflow and restricts potential groundwater recharge during wet years, thus groundwater availability does not increase during dry or normal rainfall years that follows a wet year.

3.1.2. Climate change with irrigation expansion (CC-IRR)

Increased rainfall (167 mm) and pumping (51 mm) under the CC-IRR scenario, compared to the baseline, resulted in increased ET (87 mm), streamflow (83 mm) and groundwater recharge (79 mm)

Table 6
Average annual water balance components (mm) for baseline (1980–2009) and climate change (CC, 2040–2069) scenarios. GCM refers to the average of five climate change scenarios.

Water flux	Baseline[a]	CCSM4[b]	GFDL-ESM[b]	HadGEM2[b]	MIROC5[b]	MPI-ESM[b]	GCM-Baseline (difference)
Rainfall	899	967	966	1290	1026	1082	+167.2
ET	753	776	769	840	783	825	+45.6
Streamflow[c]	163	210	215	467	261	274	+122.4
Baseflow	89	108	104	226	139	140	+54.4
Recharge	251	282	276	389	308	300	+60.0
Pumping	173	185	182	173	180	171	+5.2
Net recharge	1.5	1.6	1.7	2	1.7	1.5	+0.2

[a] The baseline scenario represents *current* groundwater withdrawals and climate.
[b] CCSM4, GFDL-ESM, HadGEM2, MIROC5 and MPI-ESM are future climate scenarios where the names represent the Global Climate Model (GCM) used to generate the climate time series.
[c] Streamflow consists of runoff plus baseflow.

(Table 7). Comparison of aggregated (30 years) results for the baseline and CC-IRR scenarios shows that increased recharge and water availability under the CC-IRR scenario was balanced by increased pumping due to irrigation expansion and increased baseflow with the end result of no significant change in net recharge (+0.2 mm, Table 7). However, net groundwater recharge decreased during many normal and dry years as compared to the baseline. Net groundwater recharge is usually negative during dry and normal years and a further reduction is likely to worsen the water availability in the hard rock aquifer region.

3.2. Groundwater dynamics

3.2.1. Climate change (CC) only

Increased groundwater recharge under the CC scenarios resulted in overall improved groundwater levels in shallow and deeper aquifers (Fig. 4). For the HadGEM2 scenario, significant rise in groundwater levels was simulated even during dry years (Fig. 4). Average May groundwater levels rose by 28 m during dry years under the HadGEM2 scenario. In contrast to HadGEM2, GFDL-ESM and CCSM4 scenarios showed slight declines in June–August groundwater levels during dry as well as wet years (Fig. 4). During wet years, dry season groundwater levels under GCM scenarios were similar to baseline. The wide range of predicted changes in groundwater levels during dry years show the GCM uncertainty in climate change impact assessments, which is discussed in greater detail under the "Uncertainties and limitations" section below. Overall, higher average (five GCMs) groundwater levels predictions indicate the possibility to partly support future irrigation expansion in the region.

3.2.2. Climate change with irrigation expansion (CC-IRR)

Increased groundwater withdrawals under the CC-IRR scenarios, compared to the baseline, resulted in groundwater declines except for some months during dry and normal years under the HadGEM2 scenario (Fig. 5). Depending on the GCM, average monthly groundwater levels in the deeper aquifer declined up to 57 m, with an average of 20 m (2040–2069). Smallest declines in groundwater levels were predicted for HadGEM2 scenario while the largest declines were predicted for GFDL-ESM and CCSM4 scenarios (Fig. 5). GFDL-ESM and CCSM4 scenarios predicted 44 m and 43 m of declines in average monthly groundwater levels during dry years. Such large predicated declines in groundwater levels indicate the increased likelihood of well drying and decreased groundwater availability in the watershed.

3.3. Well drying

Well drying can result in crop failure and reduced agriculture production. Increased recharge under the CC scenarios helped reduce well drying (tube well) duration for all year types (dry, normal and wet; Fig. 6). However, increased groundwater withdrawals under the CC-IRR scenario not only increased the frequency of well drying but also prolonged the duration (Fig. 6). During the baseline period, occurrence of tube well drying was limited to dry and normal years; however, under the CC-IRR scenarios, well drying occurred during wet years as well (Fig. 6). Compared to the baseline, dry well duration increased under all CC-IRR scenarios except HadGEM2 (−8 to 83 days/year; Fig. 6). A large increase of 43% in average annual rainfall under the HadGEM2 scenario resulted in increased groundwater recharge and improved groundwater levels as compared to the baseline even under

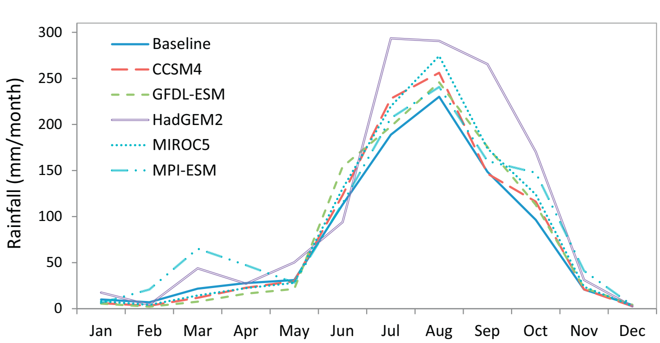

Fig. 2. Mean monthly rainfall for baseline (1980–2009) and climate change (2040–2069) scenarios. CCSM4, GFDL-ESM, HadGEM2, MIROC5 and MPI-ESM are climate change scenarios where the names represent the climate model used.

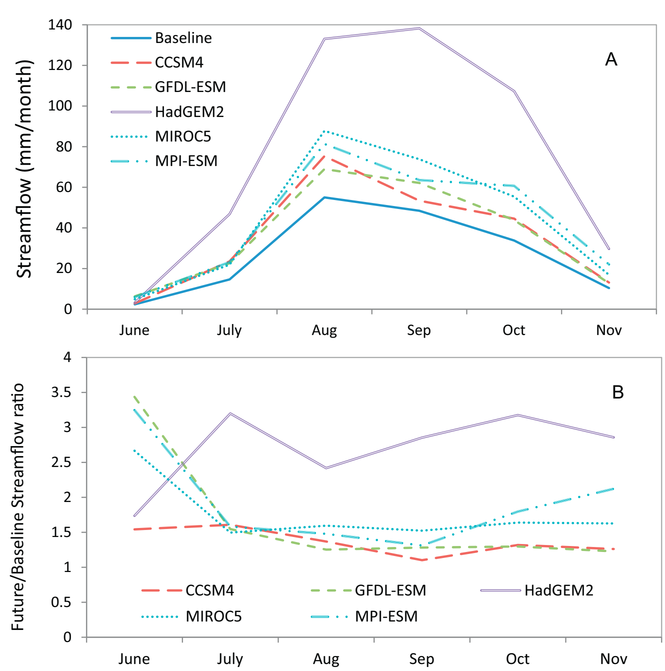

Fig. 3. Climate change effects on monthly streamflow in Kothapally watershed. A) Mean monthly streamflow (mm) under the baseline (1980–2009) and climate change (CC) (2040–2069) scenarios. B) Ratio of monthly (June–Nov) streamflow (CC/baseline). CCSM4, GFDL-ESM, HadGEM2, MIROC5 and MPI-ESM are climate change scenarios where the names represent the climate model used.

Table 7
Average annual water balance components (mm) for baseline (1980–2009) and climate change (2040–2069) with irrigation expansion (CC-IRR) scenarios. GCM refers to the average of all climate change scenarios.

Water flux	Baseline[a]	CCSM4[b]	GFDL-ESM[b]	HadGEM2[b]	MIROC5[b]	MPI-ESM[b]	GCM-Baseline (difference)
Rainfall	899	967	966	1290	1026	1082	+167.2
ET	753	811	802	892	826	869	+87.0
Streamflow[c]	163	177	184	416	220	232	+82.8
Baseflow	89	85	83	197	111	113	+28.8
Recharge	251	296	289	418	330	319	+79.4
Pumping	173	223	218	232	230	219	+51.4
Net recharge	1.5	1.3	1.5	2.3	1.8	1.6	+0.2

[a] The baseline scenario represents *current* groundwater withdrawals and climate.
[b] CCSM4, GFDL-ESM, HadGEM2, MIROC5 and MPI-ESM are future climate scenarios where the names represent the Global Climate Model (GCM) used to generate the climate time series.
[c] Streamflow consists of runoff and baseflow.

expanded irrigation acreage (Fig. 6). As a result the HadGEM2 scenario showed slight decrease (8 days/year) in dry tube well duration. Excluding for the HadGEM2 scenario, the median annual dry well duration (over all 37 tube wells in the watershed) increased by 28 to 83 days. The highest increase in annual well drying duration was predicted for GFDL-ESM (83 days) closely followed by CCSM4 (76 days). Larger increases in tube well drying duration during dry years as compared to normal or wet years (Fig. 6) will reduce the water availability in the watershed.

Open wells usually dried up in March (Fig. 7) under the baseline, but became dry earlier in January–February under the CC-IRR scenario. Although increased rainfall under the changed climate helped raise groundwater levels (CC scenario, Fig. 7), future irrigation expansion resulted in significant groundwater declines during the dry season.

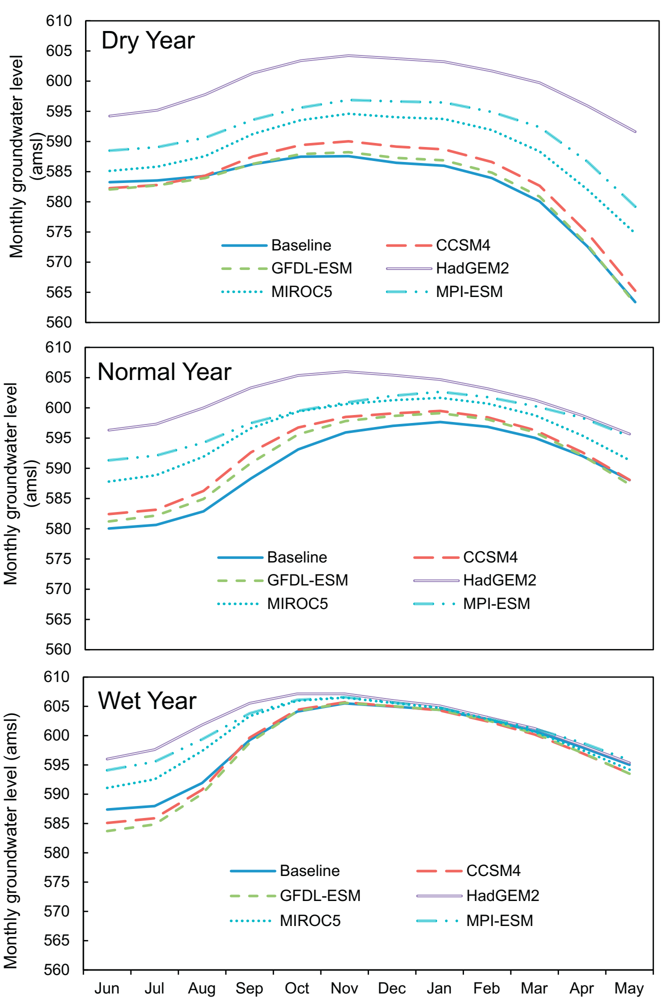

Fig. 4. Monthly average groundwater levels (above mean sea level, amsl) in a monitoring tube well (deeper aquifer) under baseline (1980–2009) and climate change (CC, 2040–2069) scenarios. CCSM4, GFDL-ESM, HadGEM2, MIROC5 and MPI-ESM are the climate change scenarios where the names represent the climate model used. Year classification was done based on the 30-year baseline rainfall 1) dry year-annual rainfall <80% average, 2) wet year-annual rainfall >120% of average and 3) normal year-annual rainfall is between 80 and 120% of average.

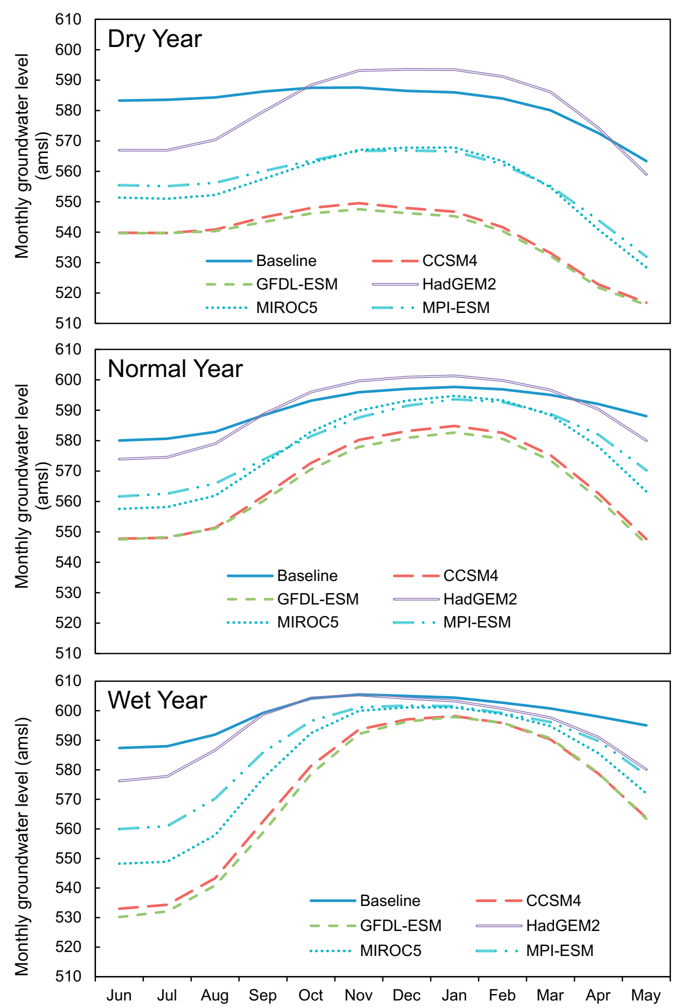

Fig. 5. Monthly average groundwater levels (amsl) in a monitoring tube well (deeper aquifer) under baseline (1980–2009) and climate change with irrigation expansion (CC-IRR, 2040–2069) scenarios. CCSM4, GFDL-ESM, HadGEM2, MIROC5 and MPI-ESM are the climate change scenarios where the names represent the climate model used. Year classification was done based on the 30-year baseline rainfall 1) dry year-annual rainfall <80% average, 2) wet year-annual rainfall >120% of average and 3) normal year-annual rainfall is between 80 and 120% of average.

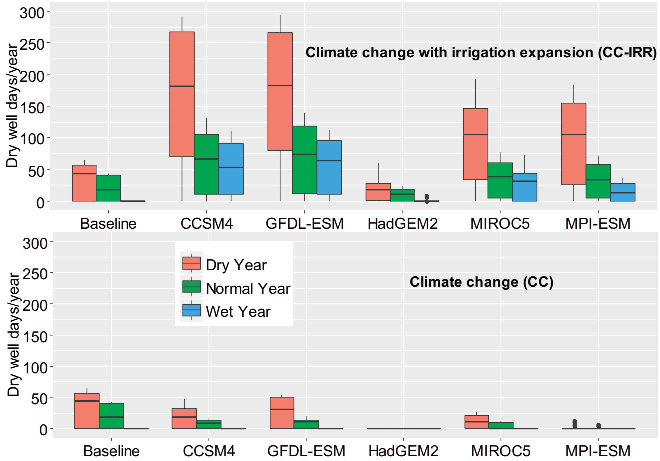

Fig. 6. Tukey's box plots for number of dry well days for 37 tube wells under baseline (1980–2009), climate change (CC, 2040–2069), and climate change with irrigation expansion (CC-IRR, 2040–2069) scenarios. Year classification was done based on the 30-year baseline rainfall 1) dry year-annual rainfall <80% average, 2) wet year-annual rainfall >120% of average and 3) normal year-annual rainfall is between 80 and 120% of average. The lower and upper end of the boxes represent first and third quartile, respectively and the whiskers extend up to the largest value no further than 1.5 × interquartile range.

Groundwater is the sole source of irrigation during the dry season and water scarcity during this period results in crop stress and yield loss. For small farmers who almost entirely depend on farm income, such yield losses negatively affect their livelihoods and exacerbate their suffering.

During the past decades, yield losses and economic hardships have resulted in severe distress to farmers in India with hundreds of them committing suicide especially in hard rock aquifer region of Telangana and Maharashtra (Dongre and Deshmukh, 2012; Rao and Suri, 2006). Model predictions suggest that this human tragedy may increase in the future unless water imbalances are addressed. *Future irrigation expansion, not changed climate, is the primary cause of predicted increase in well drying in this low storage crystalline rock aquifer. In fact, increased recharge under the projected climate change alleviated the negative impacts of irrigation expansion on well drying.* These results highlight the importance of considering societal and land use changes together with changed climate to evaluate future water availability and policy interventions.

3.4. Extreme flow events and flooding

Predicted increases in rainfall amplified annual daily maximum streamflow under the future climate scenarios. Probability of occurrence of extreme flow events (50 or 100 year return period) was predicted to increase (Fig. 8). For example, a 100-year flow event under the baseline is predicted become a five-year event under the future climate. Furthermore, the 100-year maximum flow is predicted to more than double under the average CC scenario (Fig. 8). Increased frequency and magnitude of extreme flow events under the future climate is likely to increase the flood frequency in the watershed as well as downstream locations. Massive flood in Krishna River during 2009, a >100-year flood event, claimed 319 lives, destroyed vast areas of standing crops and damaged more than a million houses causing \$6.6 billion of economic damage in the former state of Andhra Pradesh and the state of Karnataka (Killada et al., 2012; Sphere India, 2009). Predicted increase in streamflow under the future climate is likely to further exacerbate flooding damages in river basins such as the Krishna basin.

Analyses of overland water depth in low lying areas of the watershed showed that the spatial extent and duration of flooding increased under all climate change scenarios. A MIKE SHE/MIKE 11 model cell was assumed to be flooded when the depth of water in the cell exceeded 1 cm. Depending on the cell location, the flooding period increased by up to 65 days/year under the CC-IRR scenarios. The area experiencing at least a week of flooding annually increased by 15–65% under the CC-IRR scenarios as compared to the baseline. In addition to affecting crop growth and reducing the yield of many crops such as cotton, maize and tomato (Bange et al., 2004; Ezin et al., 2010), increased duration and extent of flooding is likely to make fields in the low lying areas of the watershed unsuitable for cultivation. Although water availability in low lying areas is likely to be better than uplands, potential flooding damage may lower the productivity of these areas which otherwise are more buffered against drought. Thus, intensified extreme flows and flooding on one hand and increased frequency and duration of well drying on other hand will exacerbate yield and economic losses under both hydrologic extremes in the region unless management changes are made.

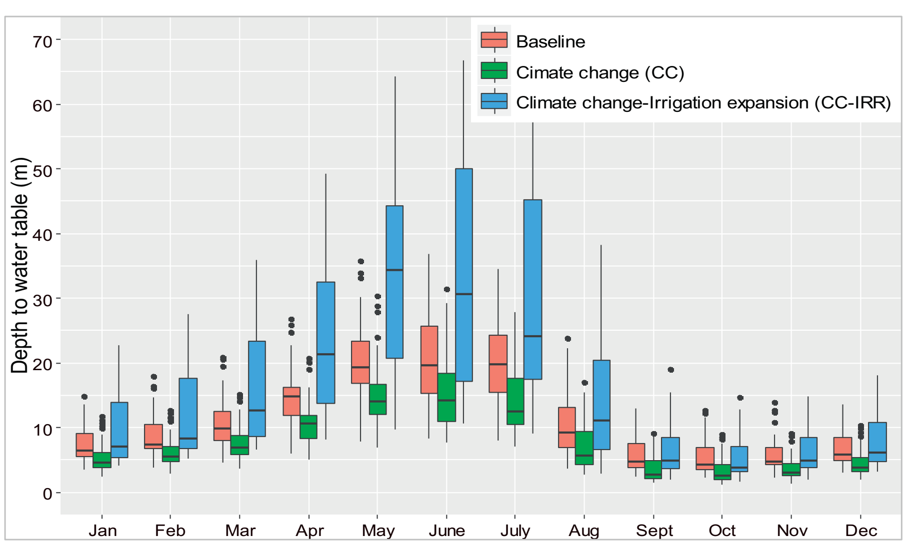

Fig. 7. Mean monthly water table depth in 31 open wells under the baseline (1980–2009), climate change only (CC, 2040–2069) and climate change with irrigation expansion (CC-IRR, 2040–2069) scenarios. A water table depth of >10 m is indicative of dry well. The lower and upper ends of the boxes represent first and third quartile, respectively and the whiskers extend up to the largest value no further than 1.5 × interquartile range.

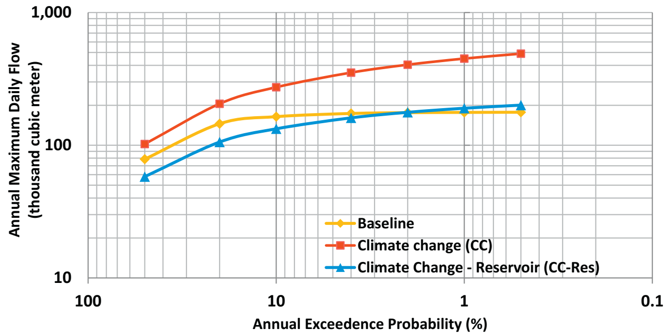

Fig. 8. Log Pearson type III flood frequency plot for Kothapally watershed under 1) baseline (1980–2009), 2) climate change (CC) only (2040–2069) and 3) climate change (2040–2069) with streamflow capture in reservoirs (CC-Res).

3.5. Future management strategies

Falling water table and well drying will affect water availability under the CC-IRR scenarios. However, increased surface flows under the future climate could be utilized to meet increased water demands in the future. Future adaptation to following three water management strategies was evaluated in MIKE SHE/MIKE11: 1) capture additional rainfall-runoff in dispersed check dams and percolation ponds to enhance groundwater recharge, 2) capture and store excess surface flows in large reservoirs at strategic locations along the streams for later use in the dry season and, 3) capture excess surface flows in large reservoirs along with 25% flood-to-drip conversion and 50% energy subsidy reduction.

3.5.1. Dispersed water storage

Increased water storage in check dams (6400 m^3, 2.2 mm) (Fig. 1) and percolation ponds (3000 m^3, 1.1 mm) raised the water table and reduced the well drying duration as compared to the current storage under CC-IRR scenarios (Fig. 9). The benefit of increased storage was much more pronounced during dry years where it reduced the annual well drying duration by 16–72 days depending on the GCM scenario. Nonetheless, groundwater levels were still lower than the baseline scenario and well drying duration remained higher than the baseline (Fig. 9). Enhanced watershed storage also increased the groundwater recharge by about 20%, but about 40% of the increased recharge was lost as baseflow. Low storage capacity of the crystalline aquifer limits the potential recharge benefits from the check dams. Although check dams and percolation ponds help improve the groundwater recharge and levels during dry and normal rainfall years, their utility is rather limited during wet years. Nearly full aquifer condition during wet years promotes baseflow. To extend the water availability form these low storage aquifers, the excess flows need to be stored for later use in dry season.

3.5.2. Reservoir storage: streamflow capture

Streamflow capture and storage at three locations along the stream was evaluated in MIKE SHE/MIKE 11. Depending on the CC scenario, average annual captured streamflow in the three stream-side reservoirs varied from 147,800 m^3 (51 mm) to 326,400 m^3 (112 mm) while maintaining the baseline flows. Evaporation from these reservoirs during August–February was estimated using the average FAO reference ET calculated for all five GCM scenarios. Assuming 30% of the stored water is lost in seepage during November–February, the remaining water could be used to irrigate the crops in the dry season starting in November. Remaining 24 to 51 mm of irrigation water could meet at least 45% of anticipated increased future irrigation demand (Table 7). To reduce the seepage and evaporation losses and maximize the water use efficiency, farmers could start using this water from November, instead of

Fig. 9. Tukey's box plots showing the effect of different management strategies on average annual dry well (groundwater depth > well depth) duration under baseline (1980–2009) and climate change with irrigation expansion (CC-IRR, 2040–2069) scenarios. Baseline scenario represents the present status/number of water storage structures. Dispersed water storage represents increased storage capacity (9400 m^3, 3 mm) of check dams and percolation tanks. Reservoir storage represents streamflow capture in large reservoirs and its use in the dry season. 25% drip indicates 25% of flood irrigated area converted to drip irrigation. 50% subsidy indicates 50% reduction in electricity subsidy (daily 3.5 h instead of 7 h). Year classification was done according to the average 30-year baseline rainfall: dry year (annual rainfall <80% of average), wet year (annual rainfall >120% of average) and normal year (annual rainfall between 80 and 120% of average). The lower and upper end of the boxes represent first and third quartile, respectively and the whiskers extend up to the largest value no further than 1.5 × interquartile range.

pumping groundwater from their own wells. Streamflow capture also reduced the magnitude of extreme flow events (e.g. 50 or 100-year flow) thereby reducing the flooding damage risk within and downstream of the watershed (Fig. 8). For example, a 5-year flow event under the future climate without reservoirs was predicted to be a 200-year flow event when reservoirs were operated. Considering predicted increases in extreme flows in the future, region-wide implementation of these large storage reservoirs could dramatically reduce peak flows and flooding damage in the Krishna basin. A local community based approach for installation and management of these structures may help to increase the water availability in the region.

Although the captured streamflow available during wet years was sufficient to fully meet the increased future irrigation demands, it was insufficient (1–15 mm) during dry years. Lower surface flows during dry years, as compared to the wet years, resulted in low capture during the dry years. Efficient irrigation (e.g. drip irrigation) must specifically be adopted to increase/sustain current production with less water during dry years.

3.5.3. Integrated supply and demand management

Provision of free electricity in several states of India promotes the wastage of groundwater and electricity thereby creating a lose-lose situation for both the state and farmers. An integrated demand (drip adoption and subsidy reduction) and supply (reservoir storage) management option was evaluated to reflect possible future changes in management and policy. Compared to no intervention, a 50% reduction in free electricity (3.5 h instead of seven), 25% drip irrigation (25% of flood irrigated areas converted to drip irrigation), and streamflow storage in large reservoirs significantly shortened the dry well duration, especially during dry years (Fig. 9). Well drying duration reduced by 18 to 156 days during dry years, depending on the GCM scenario. Despite increased irrigated area under the CC-IRR scenarios, the integrated management strategy shortened well drying duration compared to the baseline; except for the GFDL-ESM which showed slightly higher (5 days) dry well days during dry years. The integrated management almost eliminated the well drying during wet and normal rainfall years (Fig. 9). Slightly higher adoption of drip irrigation may eliminate the predicted well drying during dry years as well.

Average annual streamflow capture under CC-IRR scenarios with integrated management varied from 144,400 m^3 to 320,200 m^3 (50 mm to 110 mm) depending on the GCM. After accounting for evaporation and seepage losses, 1–14 mm and 61–247 mm of capture was predicted under dry and wet years, respectively. This is additional water available after meeting the predicted increased irrigation demand and maintaining baseline flows in the future. This captured water can provide irrigation to lands which do not have access to groundwater thereby promoting social equity. The additional income generated from dry season cash crops can help improving the livelihood of relatively poor farmers who do not have access to irrigation wells.

3.5.4. Economics of water management strategies

Dispersed water storage showed the highest benefit-cost ratios (2.9 to 19.8) followed by flood to drip irrigation conversion with subsidy reduction (1.8 to 14.4) under the CC-IRR scenario (Table 8). Remarkably high benefit-cost ratios during dry years show the importance of dispersed water storage and drip irrigation in this semi-arid low-storage aquifer region. Higher income and lower cost for dispersed water storage and drip irrigation management, compared to the reservoir storage helped increase the benefit-cost ratio. Improved groundwater levels under dispersed water storage management decreased well drying and increased water availability and crop yields especially during dry season. While calculating the benefit-cost ratios, it was assumed that irrigated area didn't change between years under all management scenarios. Although this assumption results in major yield losses during dry years under no intervention, it reduces these yield losses due to reduced well drying under the dispersed water storage and drip management thereby resulting in high benefit-cost ratios. To avoid these crop losses in future, farmers may start reducing irrigated area depending on the anticipated water availability from a well which may result in lower crop losses and hence lower benefits than estimated. Lower irrigation rate (per unit irrigated area) under drip irrigation and subsidy reduction helped reduce well drying and increase crop production and income as compared to no intervnetion. In addition to reducing the irrigation volume, subsidy reduction may result in significant electricity and money savings for the state (50% reduction in subsidy = $1 billion/year).

Lower well drying duration and crop damage and hence lower income increase during wet years, compared to dry years, resulted in smaller benefit-cost ratios for wet years. Reservoir storage option showed higher benefit-cost ratios during wet years as compared to dry years due to higher water storage and irrigated area. High capital cost of storage reservoirs lowered the benefit-cost ratios especially during dry years. Lower water capture during dry years, compared to the wet years resulted in low benefit cost ratio during dry years. Increased recharge due to seepage from these reservoirs is likely to result in higher benefits than estimated. In our calculations, seepage from the reservoirs was considered as a loss from the watershed but it will raise groundwater levels and income similar to the dispersed water storage structures (e.g. check dams). In addition, potentially reduced extreme flows due to reservoir storage are likely to reduce the flood related crop losses in low lying areas of the watershed. Provision of irrigation water from large reservoirs is likely to promote social equity in this semi-arid region by providing water access to many farmers who do not own irrigation wells. A combination of management options (e.g. drip, subsidy reduction and water storage) are likely to result in increased farm income, reduced well drying and energy consumptions thereby resulting in a sustainable co-evolution of human-water system in semi-arid India.

4. Uncertainties and limitations

Climate change impact studies using hydrologic models are subject to many uncertainties related to global climate modeling, greenhouse gases (GHGs) emission trajectories, climate downscaling and hydrologic modeling (Schewe et al., 2014; Wilby and Harris, 2006). Selection of GCMs, emission trajectories and downscaling methods affects the uncertainty in predicting future hydrology. We used five GCMs, one emission trajectory (RCP 8.5) and one downscaling method (AgMIP delta) to predict the future changes in surface and groundwater flows and availability. These five GCMs were selected for their ability to adequately predict the Indian monsoon (Ruane et al., 2015). Rainfall and temperature from these five GCMs covered a wide range of future changes predicted by a 20-member ensemble of CMIP5 GCMs that were available

Table 8
Farm income, profits and benefit-cost ratios for different management strategies under future climate with irrigation expansion (CC-IRR, 2040–2069) in the Kothapally watershed. Farm income from irrigated areas (groundwater and reservoir irrigated, no rainfed areas) was considered to calculate the income under different management strategies.

Management strategy	Year class	Income ($/ha/year)	Additional profit compared to no intervention ($/ha/year)	Cost of intervention ($)		Benefit-cost ratio
				Initial total	Annual	
No intervention	Dry	1930	–	–	–	–
	Normal	2300	–			–
	Wet	2400	–			–
Dispersed storage for enhancing recharge	Dry	2130	200	21,470	1180	19.8
	Normal	2370	70			7.3
	Wet	2430	30			2.9
Reservoir storage and associated irrigation	Dry	1940	30	582,000	32,010	0.1
	Normal	2290	120			0.3
	Wet	2910	300			0.7
25% drip, 50% subsidy and reservoir storage[a]	Dry	2520	480	611,160	35,510	0.8
	Normal	3010	310			0.5
	Wet	3030	230			0.8
25% drip and 50% subsidy[a]	Dry	2360	440	29,160	3210	14.4
	Normal	2430	140			4.5
	Wet	2450	50			1.8

[a] 25% drip indicates 25% of flood irrigated areas converted to drip irrigation and 50% subsidy indicates a 50% reduction in electricity subsidy i.e. daily 3.5 h of free electricity in place of 7 h.

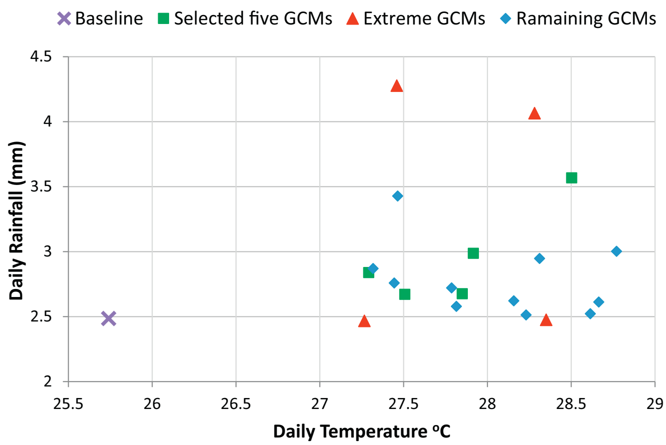

Fig. 10. Daily rainfall and temperature projections (2040–2069) from 20-Coupled Model Intercomparison Project 5 (CMIP 5) Global Climate Models (GCMs) under Representative Concentration Pathway 8.5. Selected GCMs refers to the five GCMs used in this study to predict future changes in surface and groundwater flows and availability. Extreme GCMs refer to the GCMs used to estimate wider range of future changes or uncertainty in surface flows and well drying predictions due to GCM selection e.g. high temperature high rainfall (HT-HR).

(Fig. 10). Uncertainty introduced due to GCM selection is often the largest source of uncertainty in climate change impact assessments (Kay et al., 2009). To evaluate this uncertainty, we choose four of these 20 CMIP5 GCMs to capture four extreme scenarios of temperature and rainfall: high temperature high rainfall (HT-HR); high temperature low rainfall (HT-LR); low temperature high rainfall (LT-HR) and low temperature low rainfall (LT-LF) (Fig. 10). These four GCMs were chosen to represent combination of highest and lowest predicted daily rainfall with the temperature being within ±0.5 °C of highest and lowest predicted daily temperature. Contrary to the selected five GCMs which showed increased streamflow (Table 7), the low rainfall scenarios (HT-LR and LT-LR) showed reduced streamflow in the future (HT-LR = 134 mm/year, LT-LR = 120 mm/year, Table 9) compared to the baseline (baseline = 163 mm/year). On the other hand, the high rainfall scenarios (LT-HR and HT-HR) showed higher streamflow predictions (LT-HR = 713 mm/year, HT-HR = 599 mm/year, Table 9) than the highest of five GCMs (HadGEM2 = 416 mm/year, Table 7). Similarly, MIKE SHE/MIKE 11 predictions for extreme temperature-rainfall scenarios also showed a higher increase in well drying (−21 to 131 days/year) than the five GCMs (−8 to 83 days/year). Use of multiple RCPs (RCP 4.5 and 8.5) also increased the range of streamflow and well drying predictions. MIKE SHE/MIKE 11 results for RCP 4.5 scenario with five selected GCMs showed the possibility of both lower and higher streamflow (−20 to 54 mm/year) in the future, compared to the baseline. For the RCP 4.5 scenarios, a higher increase in well drying duration (36–96 days/year) was predicted than the RCP 8.5 (−8 to 83 days/year). Overall, although additional results from extreme temperature-rainfall GCMs and RCP 4.5 scenarios showed a more worsened flooding and well drying risk in the future, these predictions were directionally similar to our results from selected five GCMs discussed in earlier sections.

Extension of our watershed-scale hydrologic modeling results to the basin scale (e.g. Krishna) carries assumptions of similar rainfall, land use and groundwater withdrawals. Differences in rainfall, percent of area irrigated and groundwater withdrawal to recharge ratio are likely to cause differences in surface flows and groundwater availability between the watershed and basin. However, the study watershed is a typical rural watershed in semi-arid region of south India and our results could be extrapolated to assess the direction of future changes in basin-scale surface and groundwater flows and availability.

Studies have shown that improved farm scale irrigation efficiency (e.g. flood to drip conversion) may reduce the return flows thereby reducing downstream water availability with the end result of no net water savings at the basin scale (Scheierling et al., 2006). However, basin scale water availability could be improved by reducing unproductive consumptive water use (e.g. soil evaporation). Shukla et al. (2014) have showed that localized wetting under drip irrigation may help reduce unproductive evaporation losses from crop row middles thereby reducing the ET by 34% compared to the surface or sub-irrigation where the entire field is wetted. Our MIKE SHE/MIKE 11 model simulations (GFDL, CC-IRR) for a hypothetical drip scenario (100% conversion of flood irrigation to drip irrigation) showed that reduced irrigation rate (61 mm/year) under the drip management also reduced the ET losses (36 mm/year) while meeting the crop water demands. Although groundwater recharge decreased by 41 mm/year under this hypothetical scenario, shallower groundwater levels due to reduced pumping resulted in higher baseflow (19 mm/year) contributions to the streamflow; this will help maintain downstream river flows. Considering potential spatial variability in rainfall, percent of area irrigated and groundwater withdrawal between the watershed and the basin (e.g. Krishna), comprehensive basin-scale studies with integrated hydrologic modeling analyses will be needed to verify the benefits of water efficient irrigation techniques at the basin scale.

5. Conclusions

Increased frequency and duration of hydrologic extremes (drought and flood), which present a risk to crops and humans, was predicted under future climate (2040–2069) with irrigation expansion in the Kothapally watershed. On an average, results from multiple GCM and RCP scenarios showed increased rainfall, recharge and surface flows in the future; however, some scenarios also showed the possibility of reduced surface flows. Intensified surface flows under the future climate will exacerbate the flooding risk especially in low lying areas; the magnitude of flow associated with a historic 100-year flow event was predicted to be associated with a five-year event in the future. *Despite increased surface flows and recharge, geologic drought and associated*

Table 9
Average annual water balance components (mm) for baseline (1980–2009) and climate change (2040–2069) with irrigation expansion (CC-IRR) scenarios. GCM refers to the average of all climate change scenarios.

Water flux	Baseline[a]	ACCESS1.0[b] (HT-LR[c])	HadGEM2-CC[b] (HT-HR[c])	INM-CM4[b] (LT-LR[c])	CSIRO-Mk3.6.0[b] (LT-HR[c])	GCM-Baseline (difference)
Rainfall	899	896	1471	893	1544	302
ET	753	782	890	793	850	76
Streamflow[d]	163	134	599	120	713	229
Baseflow	89	55	255	50	281	71
Recharge	251	259	486	252	521	129
Pumping	173	203	229	201	237	45

[a] The baseline scenario represents *current* groundwater withdrawals and climate.
[b] ACCESS1.0, HadGEM2-CC, INM-CM4, and CSIRO-Mk3.6.0 are future climate scenarios where the names represent the Global Climate Model (GCM) used to generate the climate time series.
[c] Indicates the GCM predicted temperature and rainfall as compared to the baseline; HT-LR = high temperature low rainfall, HT-HR = high temperature high rainfall, LT-LR = low temperature low rainfall, and LT-HR = low temperature high rainfall.
[d] Streamflow consists of runoff plus baseflow.

effects are likely to worsen due to offsetting effects of irrigation expansion. Conversion of much of the excess rainfall into streamflow is predicted to limit the groundwater recharge during wet years with the net effect being increased frequency and duration of well drying during dry and normal years. *Climate change effects alone are likely to mitigate the well drying; however, future irrigation expansion negated the water gains from climate change effects with the end result of worsened well drying.* Along with worsened well drying, uncertainty analyses also showed the possibility of reduced surface flows in the future. These results will aid the policymakers in developing diverse management plans to adapt to the future changes in water demands and availability. Evaluation of the combined effects of future climate change and irrigation expansion along with hydrologic and economic assessment of management alternatives have not been conducted before especially for the semi-arid crystalline rock aquifer of India. Increased well drying and reduced groundwater availability under business-as-usual (i.e. no intervention) is unlikely to sustain the needed irrigation expansion to satisfy the increased food demand related to future demographic and socio-economic changes in semi-arid hard rock aquifer regions of central and south India. Two GCM scenarios, out of five, showed that the duration of dry wells in the future may increase by four times during dry years.

Increased rainfall in the region is likely to increase the flows of the two largest rivers in south India, the Krishna and the Godavari. Augmented river flows may enhance water availability for irrigation, domestic, industrial and hydroelectric purposes as well as for surface and groundwater dependent ecosystems such as wetlands. However, unless increased surface flows are captured and stored for later use, decreased water availability due to earlier and prolonged well drying as well as increased flooding due to higher rainfall may negatively affect millions of farmers in semi-arid India. Integrated supply and demand management through capture and use of excess surface flows, conversion from flood to drip irrigation and energy policy reforms are needed to sustain the crop yields, support expanded irrigated areas and reduce flooding risk in the future. Flood to drip conversion and dispersed water storage are likely to increase farm profits significantly, especially during dry years. Increased water availability during dry years is especially beneficial since this the period of most crop damage and farmer distress in the semi-arid regions of India. Reforms in agricultural subsidy policies involving reduction in energy subsidy and implementation of integrated flood and drought management strategies will be needed to create a sustainable food-water-energy nexus in India as well as in other semi-arid regions of the world.

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